

Conduction, convection & radiation

V Vijaykiran

M.Sc., B.Ed., NET

SIGMA Physics Resource Centre

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Thermal properties of matter

There are three distinct modes of heat transfer

Conduction

- Conduction is the mechanism of transfer of heat between two adjacent parts of a body without the movement of particles of the medium from their mean position
- Gases are poor thermal conductors. Liquids have conductivities intermediate between solids and gases
- Examples : Heating of a cooking pan, heating of test tube

Convection

- Convection is a mode of heat transfer due to motion of particles of medium from one point to the other.
- Convection involves bulk transport of different parts of the fluid. It is possible only in fluids (liquids and gases)
- Example : Heating of water, cool air from an *a.c.*

Radiation

- It is the transfer of heat due to emission of electromagnetic waves
- It does not require any medium
- Example : Heat radiation from sun

Thermal properties of matter

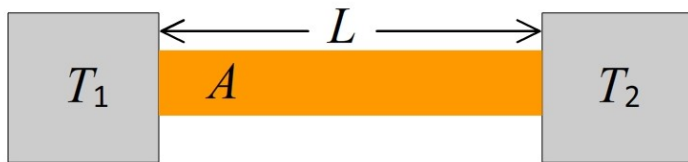
Conduction

- Conduction is the mechanism of transfer of heat between two adjacent parts of a body because of their temperature difference.
- Conduction takes place only in the presence of a medium
- Particles of the medium do not move across the regions
- Gases are poor thermal conductors
- Liquids have conductivities intermediate between solids and gases

Thermal properties of matter

Conductivity

Consider a metallic bar of length L and uniform cross-section A with its two ends maintained at different temperatures. Let temperature of cold and hot regions be T_1 and T_2 respectively. Heat losses across the sides of the bar may be neglected.



Temperature gradient is defined as the rate of change of temperature w.r.t. distance.

In steady state condition

- Temperature gradient is constant along the conductor.
- Rate of flow of heat flow i.e heat current H is proportional to temperature difference ($T_2 - T_1$) and the area of cross-section A and is inversely proportional to the length L .

$$H = K \frac{A(T_2 - T_1)}{L} \quad \text{--- i}$$

Constant of proportionality K is called coefficient of thermal conductivity of the material.

Coefficient of thermal conductivity is the heat current across a conductor of unit length, unit area of cross-section for a unit temperature gradient.

SI unit of K is $\text{J s}^{-1} \text{m}^{-1} \text{K}^{-1}$ or $\text{W m}^{-1} \text{K}^{-1}$

High K : good conductor of heat

Low K : bad conductor of heat

Thermal properties of matter

Thermal resistance of a conductor

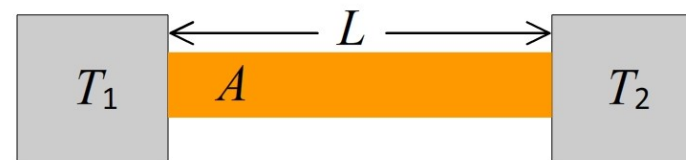
Heat current across a conductor is given by

$$H = K \frac{A(T_2 - T_1)}{L}$$
$$\Rightarrow \frac{1}{K} \frac{L}{A} = \frac{(T_2 - T_1)}{H}$$

$$\text{thermal resistance} = \frac{(T_2 - T_1)}{H}$$

Thermal resistance is the ratio of temperature difference to the heat current.

SI unit of thermal resistance is K W^{-1}



Thermal and electrical phenomenon exhibit interesting similarities. Some equivalent parameters are

- Temperature diff == potential diff
- Heat current == electric current
- Thermal resistance == electric resistance
- Junction law in heat and electricity
- Series and parallel combination of conductors

Thermal properties of matter

Applications of conducting properties in daily life

- Some cooking pots have copper coating on the bottom. Being a good conductor of heat, copper promotes the distribution of heat over the bottom of a pot for uniform cooking.
- Plastic foams are good insulators, mainly because they contain pockets of air. Such materials are used as heat insulators in cooking vessel handles and in *a.c.* pipes.
- Houses made of concrete roofs get very hot during summer days because thermal conductivity of concrete .
- In a nuclear reactor elaborate heat transfer systems are installed so that the enormous energy produced by nuclear fission in the core transits out sufficiently fast, thus preventing the core from overheating.

Thermal properties of matter

Convection

Convection is a mode of heat transfer due to motion of particles of medium. Convection involves bulk transport of different parts of the fluid. It is possible only in fluids.

The amount of heat transfer due to convection per unit time, depends on the temperature difference (ΔT) and surface area (A) of the body

$$\frac{Q}{t} \propto A(T_2 - T_1)$$

$$\frac{Q}{t} = h A(T_2 - T_1)$$

SI unit of coefficient of convection is $\text{Wm}^{-2}\text{K}^{-1}$

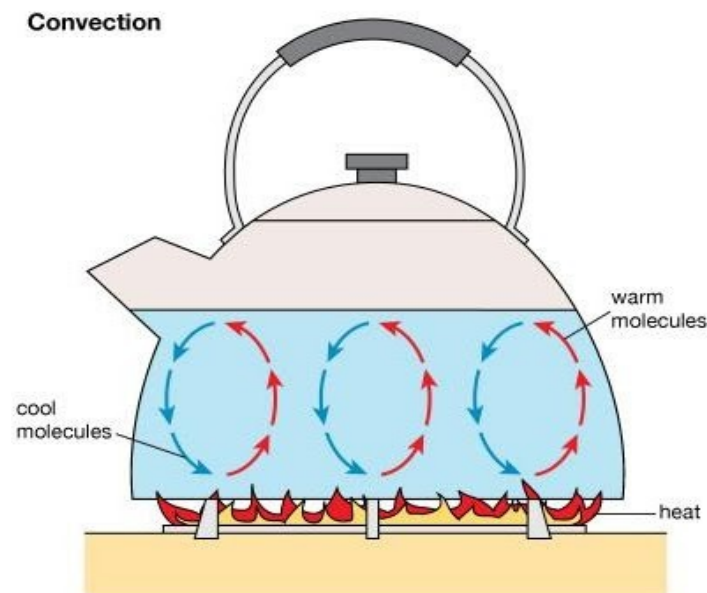
Dimensional formula of coefficient of convection is $[\text{M}^1 \text{T}^{-2} \text{K}^{-1}]$

Thermal properties of matter

Natural convection :

It takes place due to natural movement of fluid due to forces such as gravity and buoyancy.

Consider a fluid heated from bottom (as in a beaker on stove). As the lower segment of fluid becomes hot it expands and becomes less dense. It rises up due to buoyancy and is thus replaced by the upper colder segment. This process continues and the temperature of the whole fluid increases in due course of time.



Convection video clip

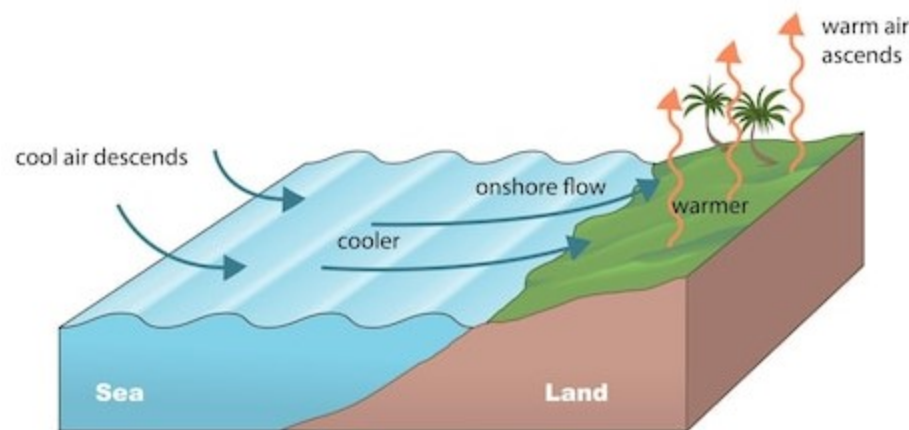
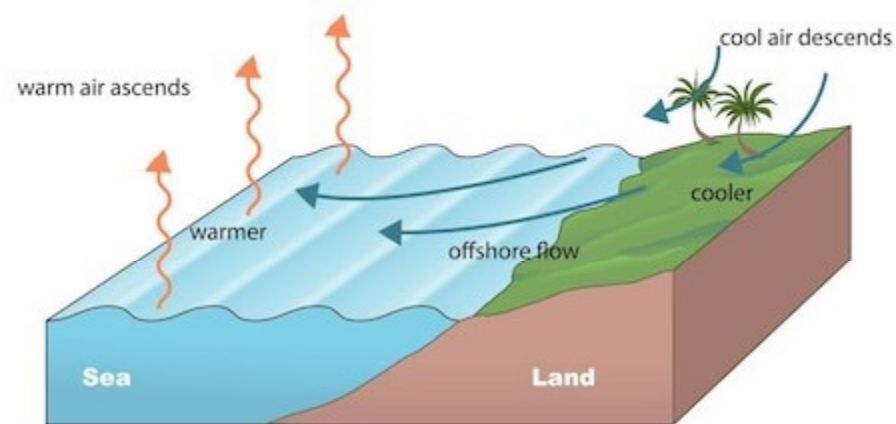
Ventilators: Ventilators are located close to the roof. Cool air enters the room through windows and hot air being less dense rises up and escapes through the ventilator. This maintains the flow of air in the room and keeps the room cool.

Thermal properties of matter

Land and sea breezes

Land breeze and sea breeze are natural examples of convection caused by temperature differences between land and sea. During the day, the land heats up faster than the sea. Warm air over the land rises, creating low pressure, and cooler air from the sea moves inland, forming a sea breeze.

At night, the land cools faster than the sea. The warmer air over the sea rises, creating low pressure there, and cooler, denser air from the land flows out to sea, forming a land breeze. These breezes show how heat causes air to move in convection currents near coastal areas.



Thermal properties of matter

Forced convection :

In forced convection, the fluid is forced to move by an external means such as a pump.

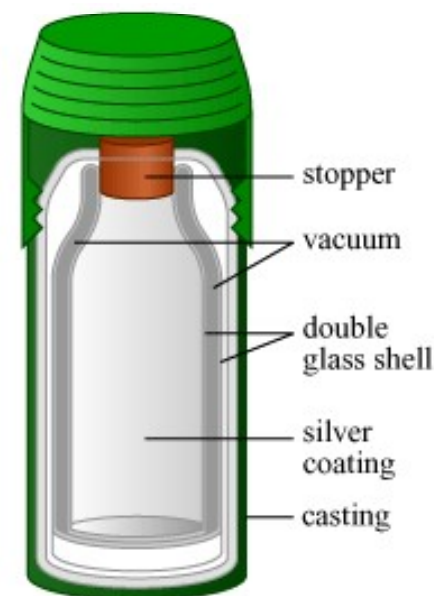
Examples of forced convection systems

- (a) forced-air heating/cooling systems in home
- (b) cooling system of an automobile engine.
- (c) human circulatory system
- (d) In the human body, the heart acts as the pump that circulates blood through different parts of the body, transferring heat by forced convection and maintaining it at a uniform temperature.

Thermal properties of matter

Radiation

- This is the process of heat transfer without involvement of any medium.
- Heat transfer takes place through the propagation of electromagnetic waves
- Radiation emitted by the sun is able to reach the earth without any medium
- Thermal radiation incident on any body is partly reflected and partly absorbed. Amount of radiation absorbed depends on the colour of the body.
- Black coloured bodies absorb and emit radiation better than bodies of other colours.
- Thermos (flask) is a double layered container with silver coating on both inner and outer walls. Region between the walls is either evacuated or filled with a thermally insulating material. The inner coating reflects the radiation thereby minimizing absorption.



Thermal properties of matter

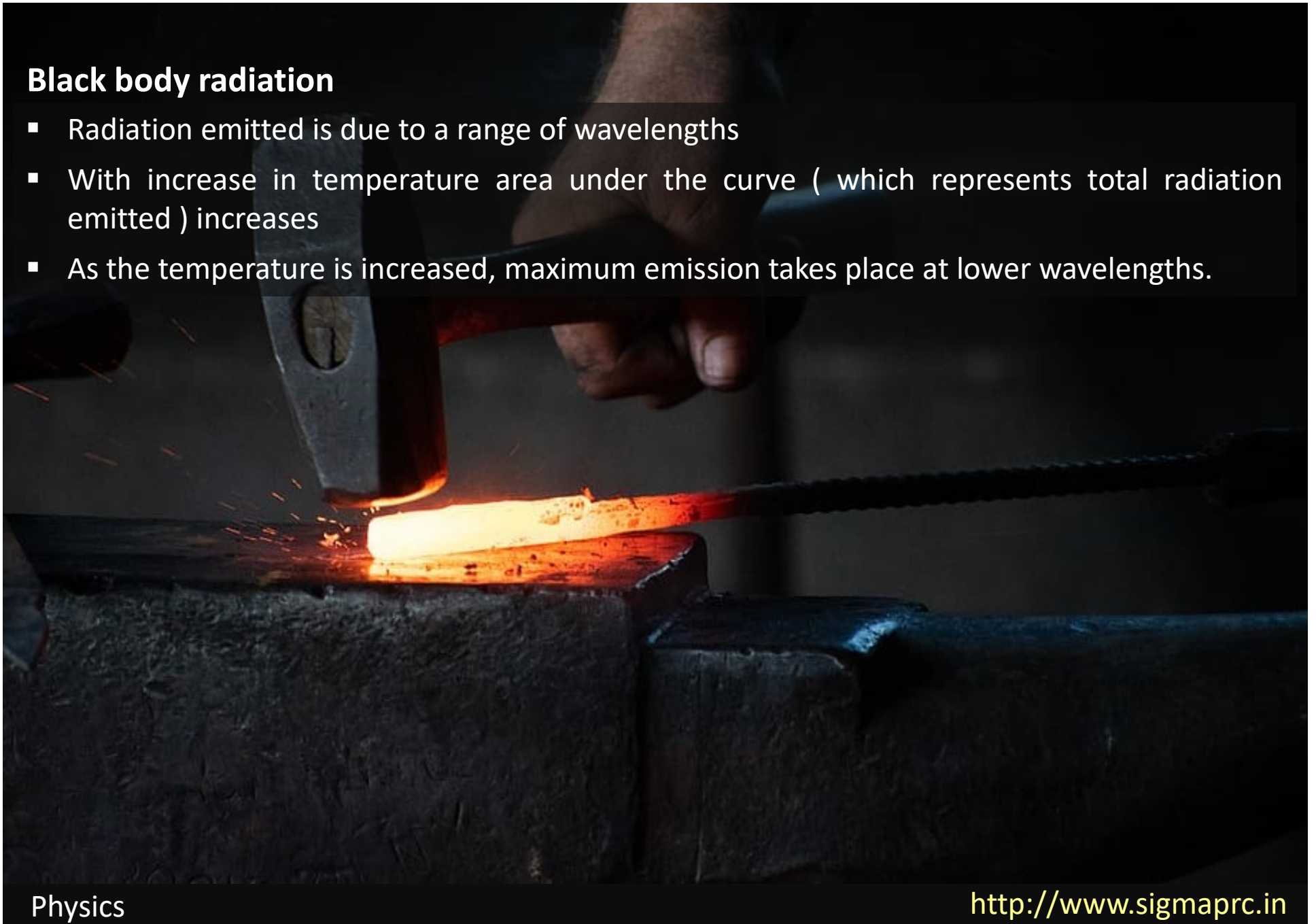
Black body radiation

- Radiation emitted by a body depends on its absolute temperature (T), area (A) time (t) and the property of the body.
- Radiation emitted by a body at any temperature consists of a range of wavelengths and the total energy radiated is the sum of all these contributions
- Energy contribution is not same for all wavelengths
- All bodies with temperature above 0K (absolute zero) emit radiation. (A body at 0°C emits radiation, as it is at an absolute temperature of 273.15K)
- Emissivity : Ratio of the radiant energy emitted by a surface to that emitted by a blackbody at the same temperature
- Emissive power : Energy of total thermal radiation emitted per unit time from each unit area of a surface at any given temperature.
- Absorptive power : It is the ratio of the energy absorbed for a given time to the energy incident on it for the same amount of time.
- Absorptive power of an ideal black body is unity (1)

Thermal properties of matter

Black body radiation

- Radiation emitted is due to a range of wavelengths
- With increase in temperature area under the curve (which represents total radiation emitted) increases
- As the temperature is increased, maximum emission takes place at lower wavelengths.



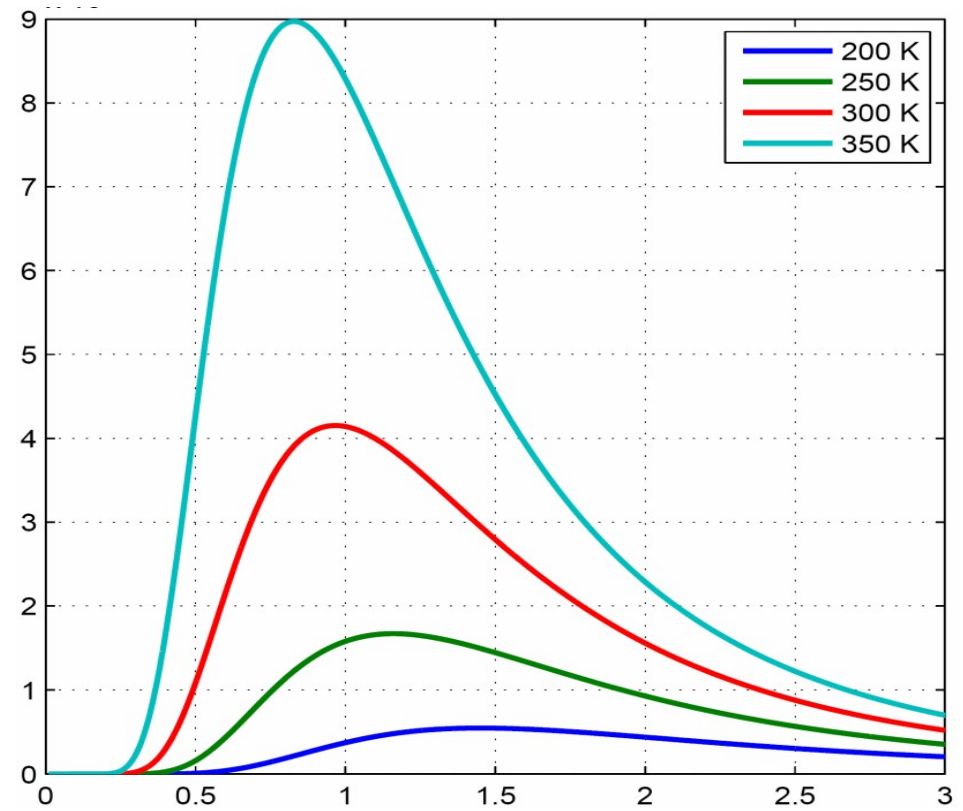
Thermal properties of matter

Black body radiation

- Radiation emitted is due to a range of wavelengths
- With increase in temperature area under the curve (which represents total radiation emitted) increases
- As the temperature is increased, maximum emission takes place at lower wavelengths.
- Wien's displacement law : Product of absolute temperature of the body and wavelength corresponding to the maximum monochromatic emissive power and is constant

$$\lambda_{\max} T = \text{constant}$$

Wien's constant = 2.9×10^{-3} mK



Monochromatic emissive power as a function of wavelength of emitted radiation

Thermal properties of matter

Quantitative relations for radiant energy

- For a perfect emitter (like a black body) total energy emitted depends on its temperature (T) and its surface area (A)

$$H = A\sigma T^4 \quad (\text{Stefan-Boltzmann's law})$$

σ is called Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$

- For a bodies other than a black body, total energy emitted is only a fraction of the above energy and given by the relation

$$H = eA\sigma T^4$$

e is called emissivity of the boy $e = 1$ for a perfect black body

- When the surroundings are at temperature T_o then the net radiant energy is given by

$$H = eA\sigma (T^4 - T_o^4)$$

Thermal properties of matter

Greenhouse Effect

It is the increase in temperature of the earth due to absorption of radiation by gases (CO_2 , CH_4 , N_2O , CF_xCl_x and O_3) called green house gases.

Earth's surface emits thermal radiation as it absorbs energy from the Sun. Wavelength of this radiation lies in the long wavelength i.e. infrared region. A large portion of this radiation is absorbed by greenhouse gases. This causes a raise in temperature of the atmosphere which leading to transfer of more energy to earth, resulting in warmer surface. This increases the intensity of radiation from the surface. The cycle repeats itself until no radiation is available for absorption. The net result is heating up of earth's surface and atmosphere. This is known as Greenhouse Effect.

Without greenhouse effect surface temperature of the earth would have been -18°C

Excessive green house effect is presently resulting in a steady raise in temperature of the earth causing global warming.

Thermal properties of matter

Cooking vessels

- Bottoms of utensils for cooking food are blackened so that they absorb maximum heat from fire and transfer it to the contents to be cooked.
- White is a good reflector of radiation. Roofs are painted white , so that they can reflect most of the light from the sun. This prevents the rooftops from getting heated up in summer.

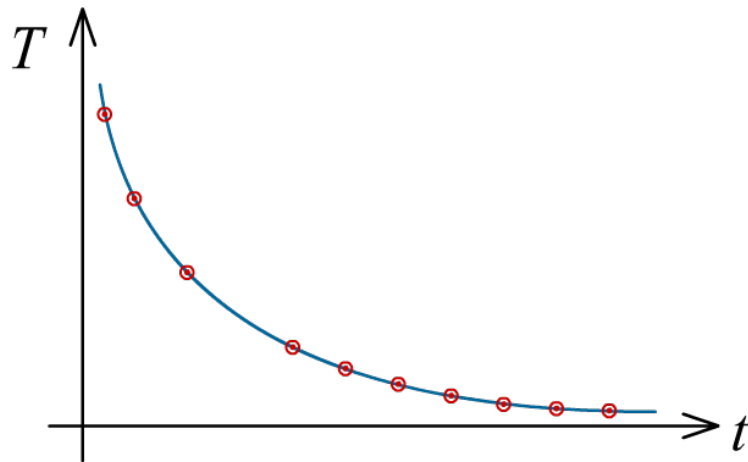
Thermal properties of matter

Newton's law of cooling

The rate of loss of heat (dQ/dt) of a body is directly proportional to the temperature difference of the body and the surrounding i.e. $\Delta T = (T_2 - T_1)$

$$-\frac{dQ}{dt} = k(T_2 - T_1)$$

k is a positive constant which depends on nature and area of surface of the body
Negative sign indicates loss of heat from the body



Graph of temperature of water as it is allowed to cool in natural surrounding

Newton's law of cooling is applicable under the following conditions only

1. Temperature difference (ΔT) is small
2. Heat loss is due to all modes i.e. conduction, convection and radiation

Thermal properties of matter

Relation for temperature of body as a function of time using Newton's law of cooling

From the Newton's law of cooling we get

$$-\frac{dQ}{dt} = k(T_2 - T_1) \text{ — i}$$

Heat lost by a body and accompanying change in its temperature is given by the relation

$$dQ = m s dT_2$$

Rate of heat loss is given by differentiating the above relation w.r.t. time, therefore

$$\frac{dQ}{dt} = m s \frac{dT_2}{dt} \text{ — ii}$$

Equating (i) and (ii) we get

$$-k(T_2 - T_1) = m s \frac{dT_2}{dt}$$

$$\frac{dT_2}{(T_2 - T_1)} = -\frac{k}{m s} dt$$

$$\frac{dT_2}{(T_2 - T_1)} = -K dt$$

Upon integration we get

$$\log_e (T_2 - T_1) = -Kt + c$$

$$T_2 - T_1 = e^{-Kt+c}$$

$$T_2 = T_1 + e^{-Kt+c}$$

The above equation gives temperature of the body as a function of time

Thermal properties of matter

`sigma`
sigmaaprc@gmail.com
sigmaaprc.in 